

Detecting Corrosion under Paint and Insulation

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Detection of corrosion through layers of paint, while also pinpointing where corrosion is present using millimeter wavelength signals at 20 GHz.

Corrosion is a major concern at the Kennedy Space Center in Florida due to the proximity of the center to the Atlantic Ocean and to salt water lagoons. High humidity, salt fogs, and ocean breezes provide an ideal environment in which painted steel structures become corroded. Maintenance of painted steel structures is a never-ending process.

Historically, steel launch towers and related ground support equipment were scheduled for sandblasting every few years, to assess whether or not corrosion was forming under paint. This has been an expensive process, due both to the labor involved in assessing the degree of corrosion, as well as the down-time incurred while sandblasting and repainting structures.

Recent developments in NASA's laboratories have led to the non-destructive evaluation and detection of such corrosion under paint, based upon a new technology for scanning and detecting such corrosion. This technology holds considerable promise for eliminating repetitive sandblasting and re-painting of ground support structures, while providing indications when it is actually time to sandblast and repaint such structures.

The new technique relies on using two millimeter wavelength signals. An early laboratory prototype is shown here, and has been successfully used for assessing corrosion under paint and insulation non-destructively in a laboratory environment.

In operation, two signal generators provide two unequal level millimeter wavelength signals. On the output of one of these generators is an RF Isolator, that prevents intermodulation products from being produced within the output circuits of the two signal generators. The two millimeter wavelength signals are then combined in a 2-way power combiner and are fed into a dual-directional coupler. The through path output from the coupler, consisting of two signals at slightly different frequencies and signal levels, are fed into a dielectric lens antenna. The two signals are then focused onto the surface of the object being evaluated for corrosion using a dielectric lens antenna.

In the presence of non-oxidized metal surfaces, only two incident signals are reflected back to the dielectric lens antenna, and into the dual directional coupler. The reverse direction sampled port of the coupler is then fed into a spectrum analyzer for further analysis.



NDE/I CUP Test Set Laboratory Prototype with painted steel test exemplar

However, in the presence of metallic oxides, that is, corrosion, a third signal is also produced. It is this third signal that provides the positive indication needed for detecting corrosion under paint.

The fundamental theory of operation relies on the fact that metallic oxide layers provide a non-linear junction to incident millimeter wavelength signals. Since the non-linear junction is inherent as a bulk property of metallic oxide layers, the presence of overlying insulation or other materials, such as pollen and dust, that do not themselves contain metallic oxides, causes no effect on the corrosion detection measurement.

However, the presence of metallic oxide layers on the surface of a painted metal structure being evaluated provides the third signal that provides a positive indication in the presence of hidden corrosion.

Three sets of test panels were used for testing the laboratory prototype. The first set of panels, painted white, were fabricated from galvanized steel panels, 12" x 18" sheet metal, 26 gauge Z. Corrosion, resulting from exposure for 3 months to a sodium chloride and water solution, was present under the painted white surface.

On the second set of panels, two sub-sets of panels with slight and nearly identical corrosion patterns to each other were created: One sub-set was cleaned before a protective coating system was applied, with only the corrosion pits remaining. The other sub-set was completely coated with an aluminum oxidation product. The aluminum test panels were constructed of 0.063-inch-thick 2024 aluminum coated with Super Koropon® fluid-resistant interior primer standard, a common space flight vehicle structural configuration. One of the sub-set of aluminum panels is shown below, with the distinctive green Koropon® primer.



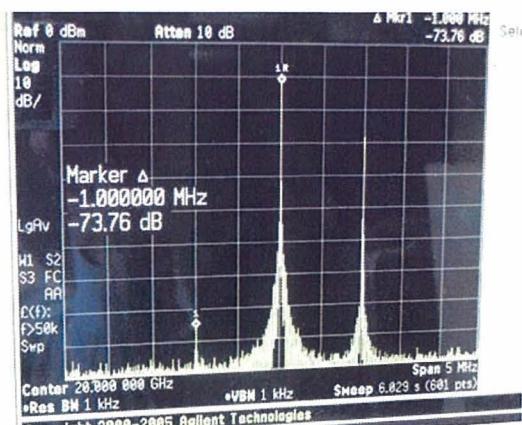
NDE/I CUP Test Set Detecting Corrosion for Aluminum Panel

Operational performance includes and surpasses the 0.008-inches thick original paint thickness requirement, surpassing 12-inches of paint or insulation thickness, enabling unanticipated use of the new corrosion-detecting technique for use in situations beyond those originally desired such as for detecting corrosion under thick blankets of insulation for pipes and tubes, such as for cryogenic applications.

Work is currently underway at Kennedy Space Center to miniaturize the technology.

Positive indications of corrosion were detected for both steel and aluminum painted panels. An operational, proof-of-concept, CUP Test Set capable of detection and localization of corrosion under paint for painted steel and aluminum materials in laboratory environments has been built.

Prior-year activities focused on development of the concepts necessary for developing an actual implementation. Subsequent work has taken this prior-year conceptual work into a real implementation, resulting in an operational, proof-of-concept, laboratory CUP Test Set.



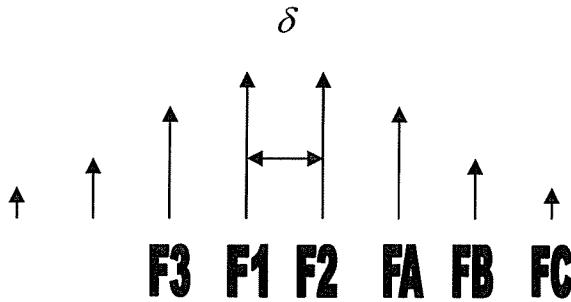
Measuring 3rd Order Passive Intermodulation Products (at F3) for Painted Steel with Corrosion under Paint



Measuring no 3rd Order Passive Intermodulation Products (at F3) for Painted Steel without Corrosion under Paint

The theory of operation of this technology relies on Passive Intermodulation Products, which are a well-known issue arising with multi-frequency communications systems.¹ When they arise, they often cause adjacent channel interference for tower-mounted arrays of antennas supporting multiple communications services.

¹ Lui, P.L., *Passive intermodulation interference in communication systems*, IEEE Electronics & Communication Engineering Journal, Vol. 2, No. 3, pp.109-118, Jun 1990.



Note the equal spacing, δ , between the two input tones F_1 and F_2 , as well as between each adjacent pair of tones, which collectively constitute all of the intermodulation products. That is to say, we can define the equal spacing between all tones as being the spacing of the two input tones, or of any other pair of adjacent tones, as:

$$\delta = F_2 - F_1$$

Inband third order passive intermodulation products are of the form:

$$\begin{aligned} 2F_2 - F_1 &= F_2 + (F_2 - F_1) = F_2 + \delta \\ 2F_1 - F_2 &= F_1 - (F_2 - F_1) = F_1 - \delta \end{aligned}$$

Now, consider the inband products at $FB = F_2 + 2\delta$ and at $FA = F_1 - 2\delta$. What products are these?

They are the fifth order products, for:

$$\begin{aligned} F_2 + 2\delta &= (F_2 + \delta) + \delta \\ &= (F_2 + (F_2 - F_1)) + \delta \\ &= 2F_2 - F_1 + \delta \\ &= 2F_2 - F_1 + F_2 - F_1 \\ &= 3F_2 - 2F_1 \end{aligned}$$

and

$$\begin{aligned} F_1 - 2\delta &= F_1 - 2(F_2 - F_1) \\ &= F_1 - 2F_2 + 2F_1 \\ &= 3F_1 - 2F_2 \end{aligned}$$

and, since the coefficients 3 and 2 sum to 5, in each of the two equations, this means these are fifth order products.

Similarly, the product at $FC = F_2 + 3\delta$ is one of the Seventh Order products, for:

$$\begin{aligned} F_2 + 3(F_2 - F_1) &= F_2 + 3F_2 - 3F_1 \\ &= 4F_2 + 3F_1 \end{aligned}$$

and the coefficients 4 and 3 add to 7, indicating that this is one of the 7th Order Passive Intermodulation Products.

The hypothesis is that the products in the figure, seen with equal spacing, spaced alongside F_1 and F_2 , are the spectral indications of the **odd-order** Passive Intermodulation Products.

To prove this hypothesis is true, consider the general case:

$$\begin{aligned} F_2 + n\delta &= F_2 + n(F_2 - F_1) \\ &= (n+1)F_2 - nF_1 \end{aligned}$$

The *Order* of an intermodulation product is defined as the sum of the coefficients, that is:

$$Order = (n+1) + n = 2n + 1$$

But, this value, of $2n + 1$ is odd for all $n \geq 1$! So, it is true that the products on the right hand side of the figure, equally spaced to the right of F_2 , are only the odd products.

Likewise, for the equally spaced tones on the left hand side of the figure, representing the lower frequency products:

$$\begin{aligned} F_1 - n\delta &= F_1 - n(F_2 - F_1) \\ &= F_1 - nF_2 + nF_1 \\ &= (n+1)F_1 - nF_2 \end{aligned}$$

and, again, we define the *Order* of the product as the sum of the coefficients, that is:

$$Order = (n+1) + n = 2n + 1$$

But, this value, of $2n + 1$ is odd for all $n \leq -1$! So the hypothesis is true for the products on the left hand side of the F_1 and F_2 pair that were shown previously in the figure. Since the hypothesis is true

for all the products to the right of the F_1 and F_2 pair, and is additionally true for all intermodulation products appearing to the left of the F_1 and F_2 pair, it is true across the entire spectrum. Hence, all the evenly-spaced products in the spectral analyzer display, besides just the F_1 and F_2 pair, are odd-order intermodulation products.

The only passive intermodulation products seen in a narrowband system are odd-order products. They are also the only intermodulation products that matter for detecting corrosion using the technique described in this paper. In practice, only **one** of the two 3rd Order products need even be considered for the case of employing two-**unequal** level input tones for implementing an F_1 and F_2 scanning signal pair of tones. Using unequal scanning tones is advantageous because although it causes one of the two 3rd Order Products to be of considerably lesser magnitude than the other 3rd Order Product, more importantly, the use of unequal tones significantly reduces the power consumption necessary for generating a response in the presence of corrosion by roughly $\frac{1}{2}$, since but one large signal interacting with a much smaller signal will suffice to generate the single 3rd Order Product necessary for detecting corrosion under paint. With power efficiencies running only a few percent to generate millimeter wavelength signals, eliminating the need to generate but one tone instead of two is a major advantage.

Fortunately, the use of unequal tones does not change the spectral relationships in the frequency domain; it only changes the magnitudes of the two odd order products of the same order, with the largest, most detectable signal, being found on the side where the largest of the F_1 and F_2 pair resides. Hence, for setting F_1 , the lower frequency tone to, say, 15 dB above the power level of F_2 , the only 3rd Order Product likely to be visible on the spectrum analyzer display will be on the lower frequency side of the F_1 and F_2 pair, offset by the same spacing, δ , as exists between the F_1 and F_2 pair, at F_3 . (There is another 3rd Order intermodulation product that exists on the high side, under the noise floor of the spectrum analyzer typically, unless resolution and video bandwidths are both reduced to very small values, and the sweep time is increased to a very long time period)

The actual microscopic physics principles responsible for the presence of such non-linear passive intermodulation products are complex and poorly

understood. Nonetheless, there have been attempts documented in the literature to understand the phenomenon and all of the following mechanisms are believed responsible for the generation of passive intermodulation products:¹

- 1.) Electron tunneling and semiconductor action through thin oxide layers separating conductors at metallic contacts
- 2.) Micro-discharges between micro-cracks and across voids in metals
- 3.) Nonlinearities associated with dirt and metal particles on metal surfaces
- 4.) High current densities at contacts
- 5.) Nonlinear resistivity of carbon fibers
- 6.) Nonlinear hysteresis effects in ferromagnetic materials

For steel surfaces, all but number 5 are clearly at play for creating the passive intermodulation products needed for detecting corrosion under painted surfaces, as the carbon and iron that together collectively become steel are typically not arranged as fibers but as tiny domain areas when examined in cross-section – however, on a small enough scale, even these tiny domains often do exhibit slight fibrous resemblances, hence, even number 5 could be slightly at play for steel materials.

For aluminum surfaces, all but numbers 5 and 6 are at play, as there is typically no carbon, but only silicon, arsenic, and other elements in tiny amounts within commercially-produced aluminum. In either case, numerous mechanisms are available for generation of passive intermodulation products. Whatever the cause, it is the presence of these numerous mechanisms as well as perhaps other mechanisms that enable the detection of corrosion under paint, which, in its most simplest form, is often a manifestation of the presence of oxide (corrosion) layers on aluminum or steel. Likewise, the presence of corrosion on other metals could also presumably be detected, although the power levels required for detecting corrosion with other metals and metallic alloys might require higher power levels than has been found to be needed for detecting corrosion under paint for steel and aluminum.

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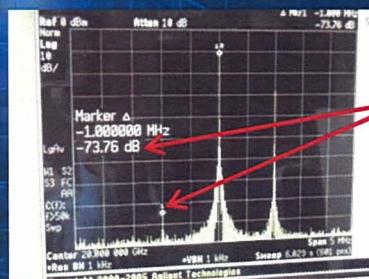
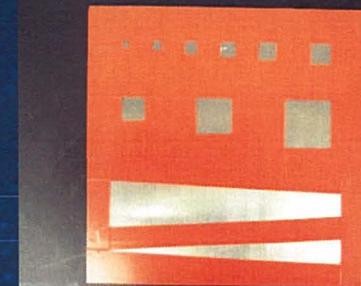


Need for Detecting Corrosion Under Paint

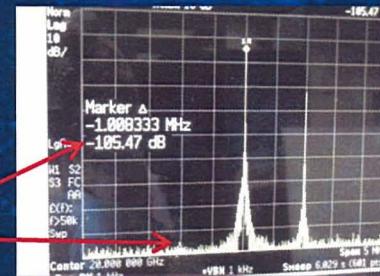
- Corrosion is a major concern at the Kennedy Space Center
 - High humidity, salt water lagoons, Atlantic Ocean, Ocean breezes
 - Numerous steel launch tower structures and steel Ground Support Equipment are at KSC
 - Continuous sandblasting and painting of steel structures is required
 - Expensive maintenance costs
- Practice has been to sandblast paint to determine whether or not corrosion has deteriorated underlying steel structures, requiring repainting whether or not structure actually had corrosion present

Development History of CUP Technology

- This NDE/I technique was first announced in a 2004 NTR resulting from Emerging Comm. technology.
- Technique was experimentally validated in FY2009, with theory and performance documented in a detailed September 2009 NASA Technical Memo.
- Able to detect corrosion & pitting under paint for painted steel & painted aluminum materials
 - Maximum coating depth limitation is approximately 14-inches
 - Technique is suitable for inspection of structures (bridges, ships, etc.), insulated steel pipelines (oil industry), and insulated cryogenic pipes.



Indicating No
Corrosion



Detecting
Corrosion



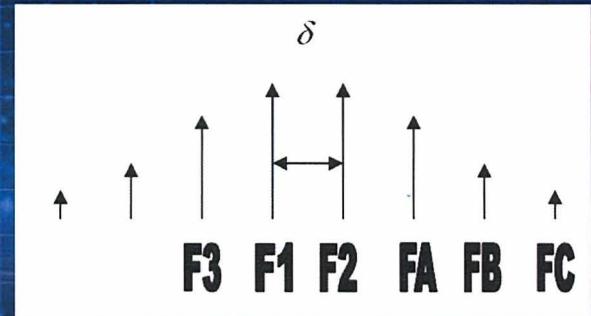
Theory of Operation

- Passive Intermodulation Products have long been noted with multi-frequency communication systems
- Passive Intermodulation Products depend on one or more mechanisms being present:
 - Electron tunneling and semiconductor action through thin oxide layers separating conductors at metallic contacts
 - Micro-discharges between micro-cracks and across voids in metals
 - Nonlinearities associated with dirt and metal particles on metal surfaces
 - High current densities at contacts
 - Nonlinear resistivity of carbon fibers (nanotubes)
 - Nonlinear hysteresis effects in ferromagnetic materials
- These properties mean that passive intermodulation products can be used to detect corrosion, which is just a form of oxide layers.



What are Intermodulation Products?

- Intermodulation products are generalized sum and difference products produced in the frequency domain resulting when two signals, F_1 and F_2 , are present



- Equal Spacings seen on a spectrum analyzer display are for odd-order inband products



Order of Products

- The order of products is equal to the sum of the multiplying coefficients
- Only odd-order products appear in-band
- Closest products are 3rd Order Products, next closest products are 5th Order, then 7th, 9th, ..., etc.

$$\delta = F_2 - F_1$$

Inband third order passive intermodulation products are of the form:

$$2F_2 - F_1 = F_2 + (F_2 - F_1) = F_2 + \delta$$
$$2F_1 - F_2 = F_1 - (F_2 - F_1) = F_1 - \delta$$

Now, consider the inband products at $FB = F_2 + 2\delta$ and at $F_1 - 2\delta$. What products are these?

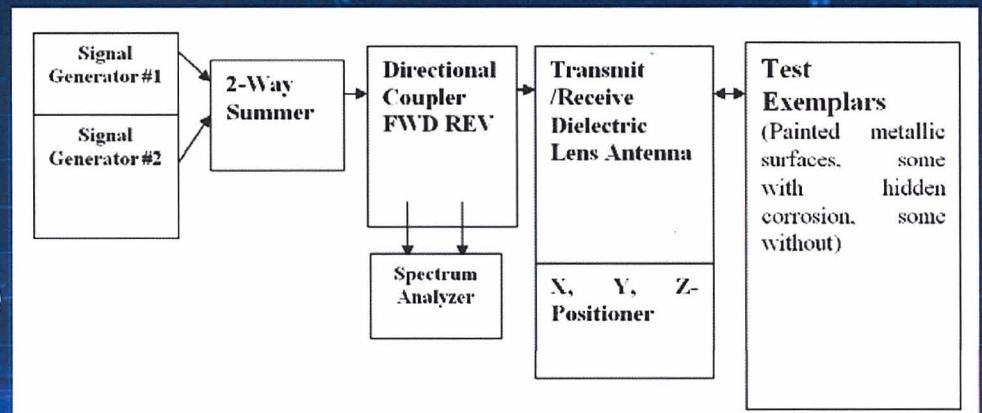
They are the fifth order products, for:

$$F_2 + 2\delta = (F_2 + \delta) + \delta$$
$$= (F_2 + (F_2 - F_1)) + \delta$$
$$= 2F_2 - F_1 + \delta$$
$$= 2F_2 - F_1 + F_2 - F_1$$
$$= 3F_2 - 2F_1$$



Detection Hardware Test Set

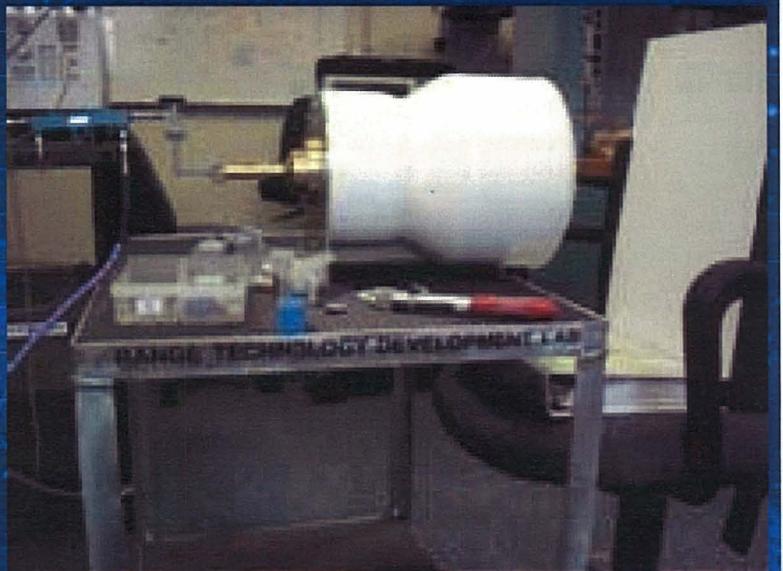
- 2 signal sources
- 2-Way Summer
- Dual-directional Coupler
- Transmit/Receive Dielectric Lens Antenna
- Spectrum Analyzer





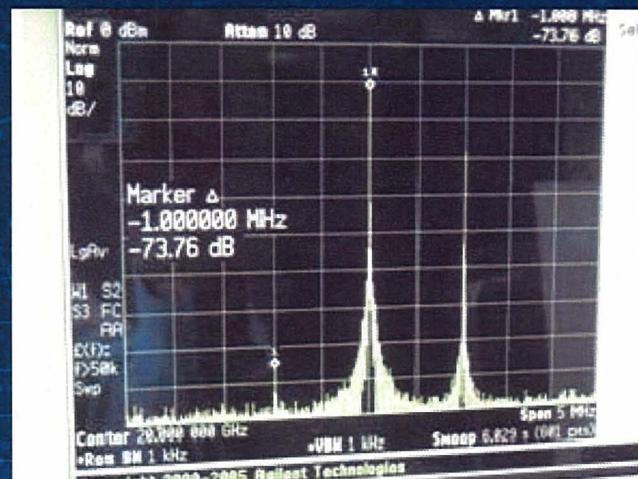
Hardware Implementation

- Frequency is currently 20.000 & 20.001 GHz
- A Dielectric Lens Antenna focuses dual-frequency beam to 1-inch dia. spot size at a distance of 12-inches from the antenna, exciting the surface to be inspected and receiving reflected signals

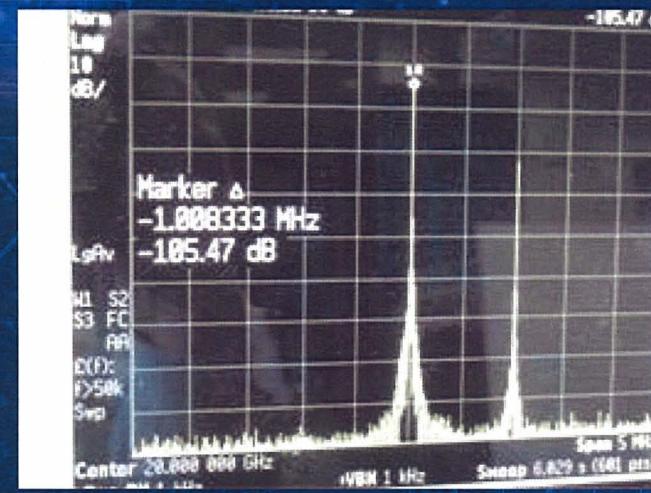


Spectrum Analyzer Display with and without Corrosion

- Unequal level (15 dB different) amplitude tones used for F1 & F2 to reduce power relative to using two equal level tones

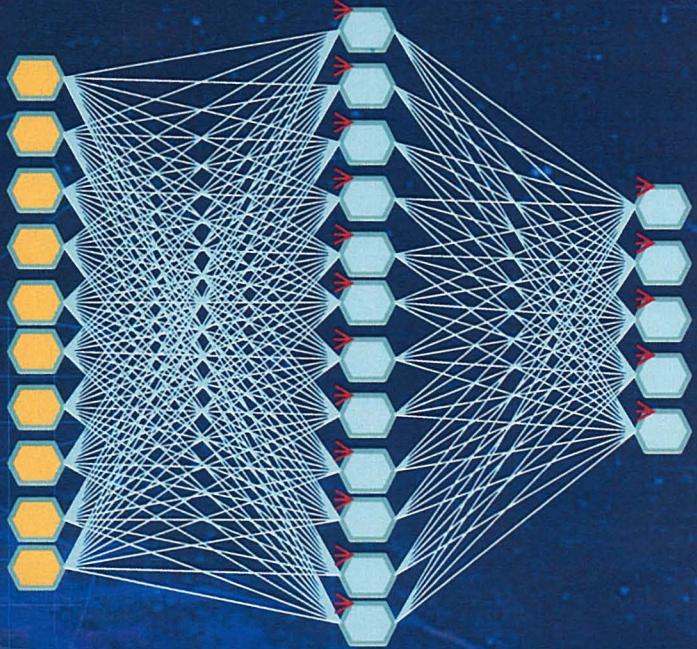


- When corrosion is present, a 3rd Order Product is visible
- When corrosion is not present, there is no 3rd Order Product

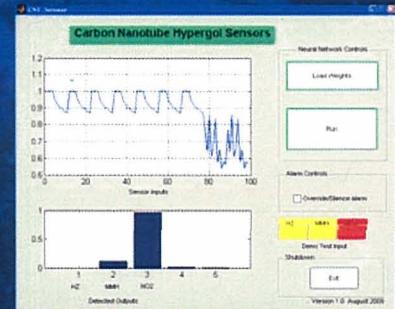


Non-Destructive Evaluation (NDE)/Inspection of Corrosion Under Paint -- Next Steps

- Miniaturize and package design for portable use
- Collect training data, characterizing corrosion vs. pitting on steel and aluminum materials
- Train a Neural Network to recognize patterns corresponding to pitting vs. corrosion vs. thickness of corrosion/pitting
- Develop a Graphical User Interface (GUI) for an Embedded Software application to operate Neural Network and display estimates of corrosion, pitting, and, possibly, depth of corrosion



A previous example of a Neural Network GUI using the same Neural Network kernel, shown above.





Video showing test

- Separate video to be shown of hardware in use to test NY Metropolitan Museum of Art test samples (painted metal plates, fabricated to simulate 18th Century art)